# Using Adaptive Mesh Refinement to Study Grid Resolution Effects for Shock/Boundary-Layer Interactions

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AIAA Aviation Forum

When you're up to your neck in alligators,
it's difficult to remember that your intent was to drain the pool

Simple task: Grid converged answer on bump flowfield for $R_{ij}$ model

1. Use AMR (push it to its limits, find out how it works as well)
2. Start with already reasonable grid (See how reasonable it was)
3. Vet methodology to get "Continuous answer"(Sharpen the saw)

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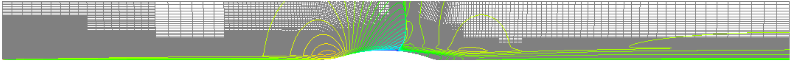
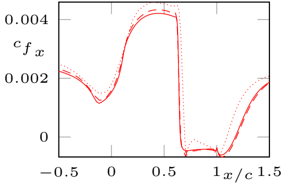
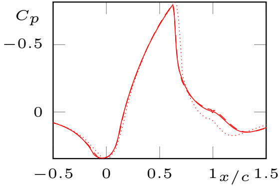
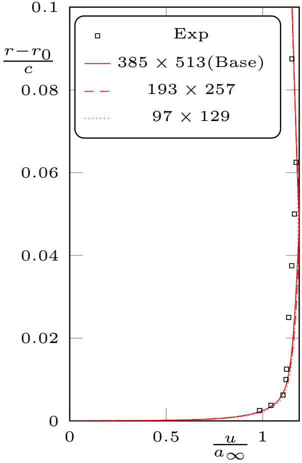





Skin friction




Pressure coefficient




Velocity $x/c = 0.625$

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Outcome:

1. $u_i$, $R_{ij}$ keep changing (Implementation bug? – no)
2. try simpler $\nu_t$ model ("Emergent behaviour" in $R_{ij}$ model? – no)
3. try verified $\nu_t$ implementation ( Model-development code bug? – no)

   Same behavior for SA-noft2 & SST models in "production overflow"!

4. Eventually, pool drained. (Along with two adjacent pools)

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# Scope/Implications



## Scope

- Scope: inherently "academic" (turbulence model development)
  - Continous limit? mathematical model requirement
  - Limited to non-exotic models (here) $\nu_t$ models inherently "nice"
  - Work (the initial pool) was for next generation model development
  - Turbulence modeling implications scrupulously avoided
  - Of interest if considering AMR (what to look for, how to)
- Implications(from the cases studied here)
  - Surface quantities (even $c_f$) grid converge first
  - Velocity profiles (and the functions they control) converge later
  - Shocks always benefit.
  - Separated zones benefit
  - Expansion fans benefit
  - Boundary-layer edges benefit (usually unimportant)

  Bottom line: New models will benefit most (flow history driven, less diffusive)

# Computational Methodology/Experiments

Solver: Overflow 2.2k[modified and production]

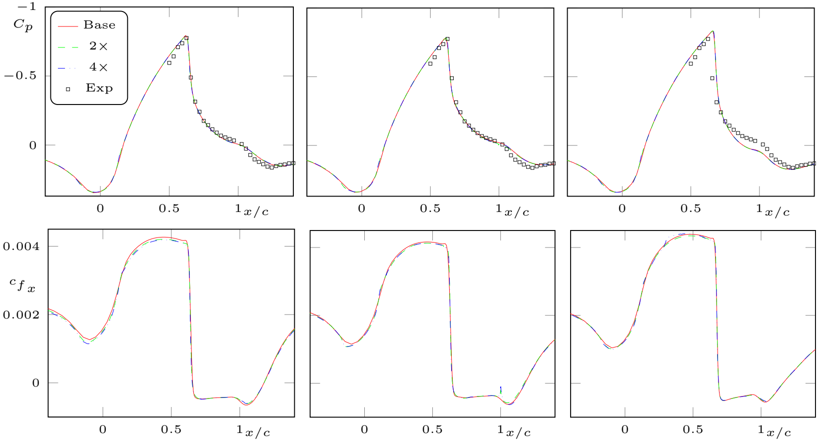
- Matrix dissipation (AIAA 2001-2664)
- No multigrid (but grid sequencing/full multigrid always)
- Error reduction, not time to solution, was governing goal ($\mapsto$ continuous solution)
- AMR Sensor: second undivided difference function (linearity)
- Near body refinement, converged at each grid level
- Solutions agreed with uniform refinement two levels deep

Flowfields/Experiment:

1. Bachalo/Johnson Bump ($M_\infty = 0.875$)
2. Brown/Brown/Kussoy Flare ($M_\infty = 2.89$)
3. Driver CS0 ($M_\infty = 0.1$)

# Bachalo-Johnson bump — surface stress



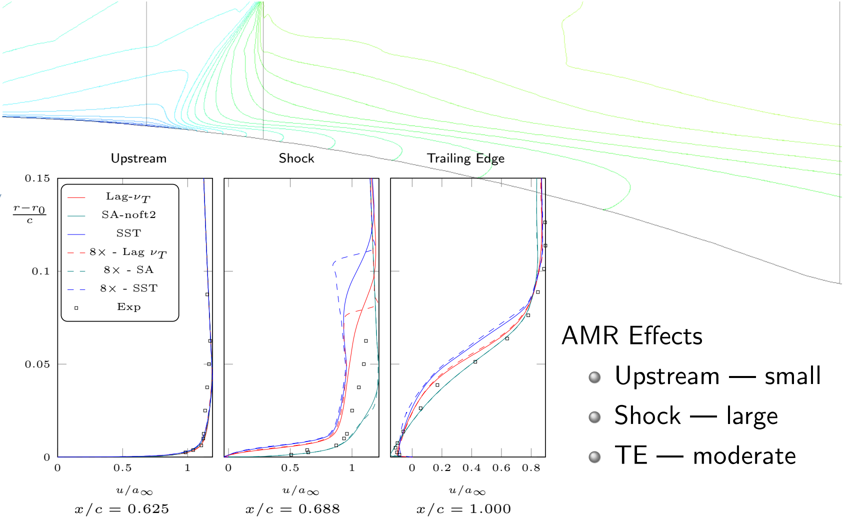



Lag-$\nu_T$ SST SA-noft2

- Coarsest grid here is finest on previous slide (Baseline)
- Skin friction and pressure completely define surface state
- Converged, with nothing happening with two grid refinements
- Answers agree with uniform refinement results to these levels

# Velocity profiles showing the effect of AMR






AMR Effects

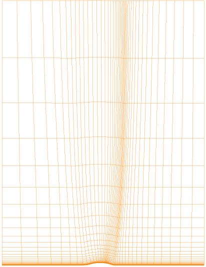
- Upstream — small
- Shock — large
- TE — moderate

- Separated region velocity field changes (8x "Converged")
- Shock structure continues to clarify with further refinement
- $\lambda$ structure (with weak downstream shock) for Lag-$\nu_t$ and SST

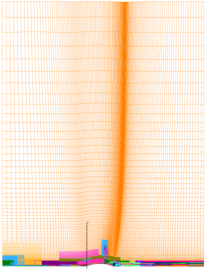
# Bachalo-Johnson bump grid and solution



AMR for SBLI
Olsen, Lillard
Introduction
Method/Flows
Results
Bachalo-Johnson Bump
Brown-Brown-Kussoy Flare
Driver CS0 Flow
Conclusions

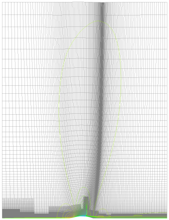


Baseline (every 4th )

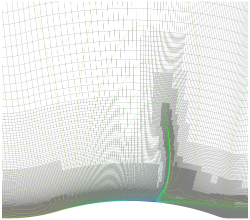


AMR , refinement level 3

Grid



Overall



Bump Closeup

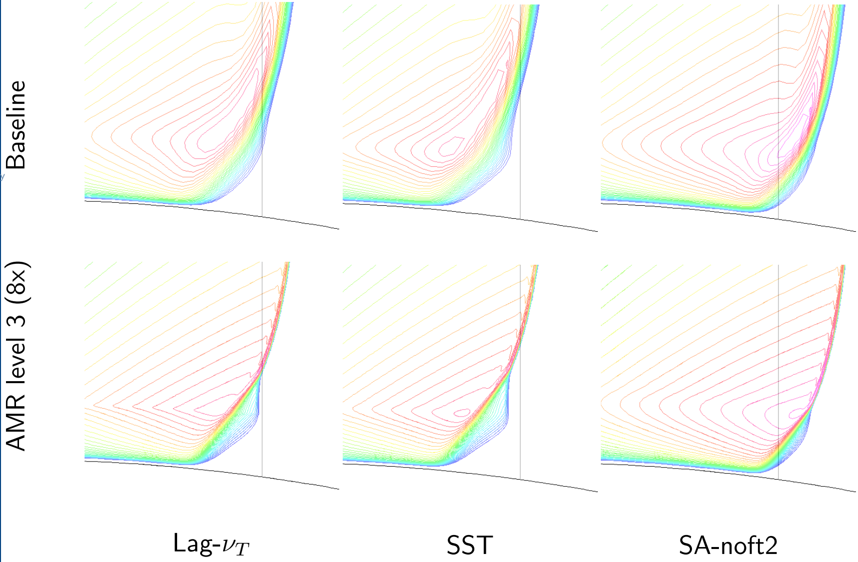
Solution($\rho$)

Baseline grid

- Already pretty fine
- Concentration – bump, downstream
- Farfield already coarse

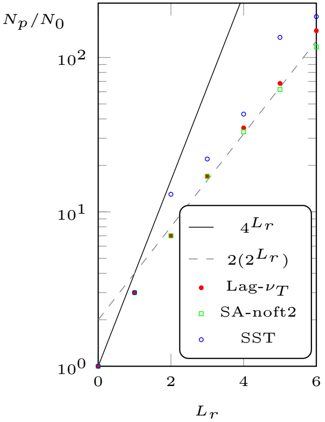
AMR grid refinements

- Boundary layer (edge)
- Shock
- Separated zone
- Post shock



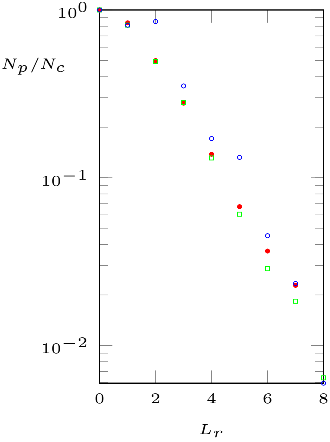
Baseline
AMR level 3 (8x)
Lag-$\nu_T$
SST
SA-noft2

AMR/baseline




Cost

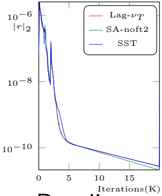
AMR/uniform




Efficiency

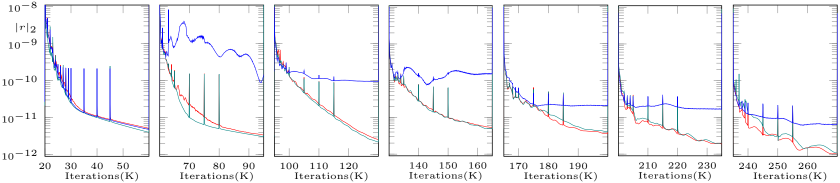
# Residual History(Grid Refinement Level $L_r$)





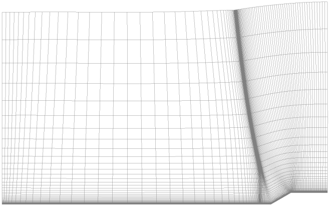

Baseline

- Iterations required don't increase with $L_r$
- 20K iterations at each new $L_r$, +10K insurance
- 20K iterations to get baseline (include grid sequencing)
- Reasonable, predictable cost ($t_{CPU}/N_{grid}$ insensitive)
- Well converged solutions ($\mapsto$ continuous)

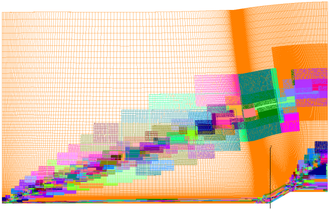



$L_r = 1$ $L_r = 2$ $L_r = 3$ $L_r = 4$ $L_r = 5$ $L_r = 6$ $L_r = 7$

Grid

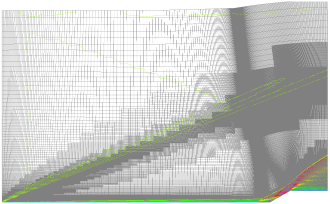


Baseline (every 4th )

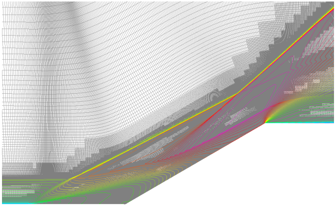


AMR , refinement level 3

Solution($\rho$)



Overall



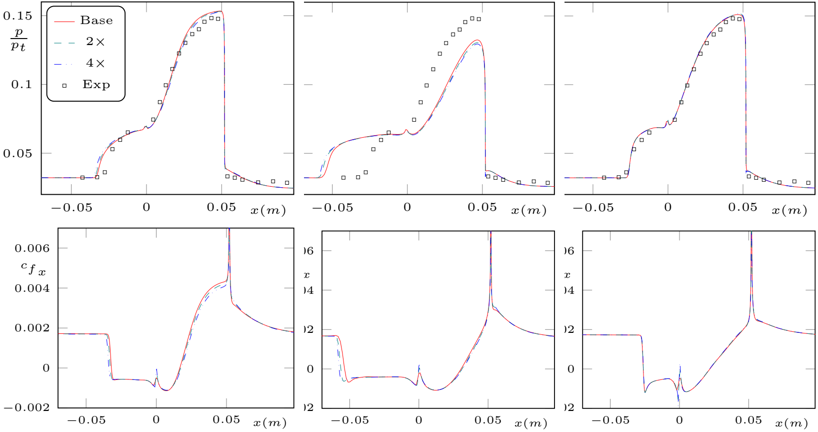
Corner Closeup

AMR grid refinements:

- Boundary layer edge
- Shocks
- Separation/Reattachment
- Expansion Fan

# Brown-Brown-Kussoy Flare — surface stress

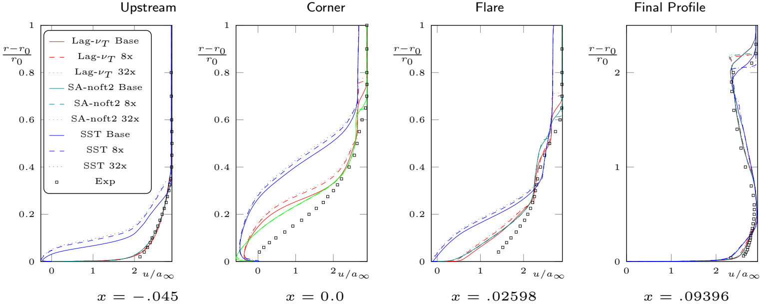





Lag-$\nu_T$ SST SA-noft2

- Skin friction and pressure completely define surface state
- Grid converged, with separation fixed at $2\times$ refinement

# Velocity profiles showing the effect of AMR



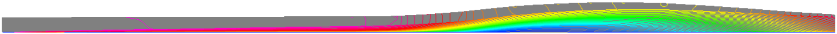

AMR Effects:( Upstream — small, Separated — large, Exit — moderate)

- $L_r \geq 1$ AMR solutions in general agreement (except for...)
- Separated region $L_r \geq 3$ in general agreement (except for...)
- Shock regions continue to evolve (shocks sharpen)

# Driver CS0 - AMR Grid and Solution



AMR grid system, refinement level 3



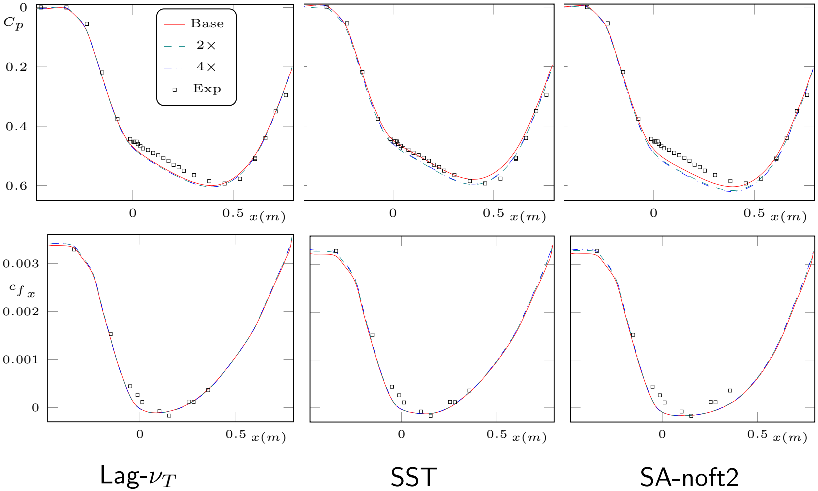
solution (axial velocity), refinement level 3

AMR grid refinements

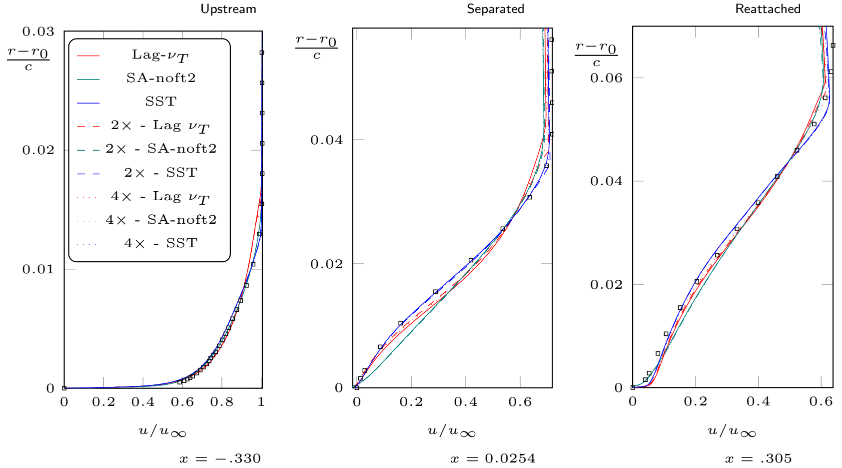
- Boundary layer
- Shear layer
- Refinement "everywhere"
- More what was expected with AMR (no shocks, $C_\infty$ thinking)

# Driver CS0 Flow— surface stress






- Baseline Solution already close, $L_r \geq 1$ tiny changes
- Skin friction and pressure completely define surface state
- Converged, with small changes after one grid refinement

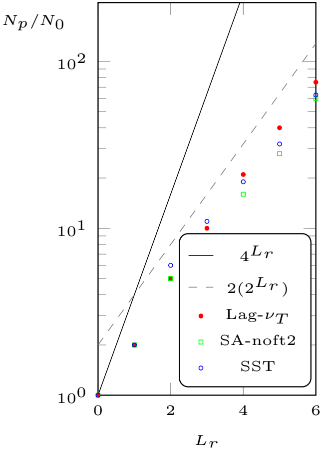



AMR Effects: Upstream — small, Separated & Downstream — moderate

- Boundary-layer edge/shear layer small changes
- Much smaller changes overall
- No shocks $\mapsto$ less surprise

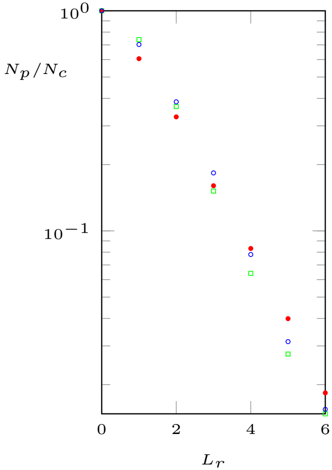
# AMR grid size comparisons – Cost/Efficiency

AMR/baseline




Cost

AMR/uniform

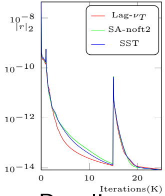



Efficiency

# Residual History(Grid Refinement Level $L_r$)

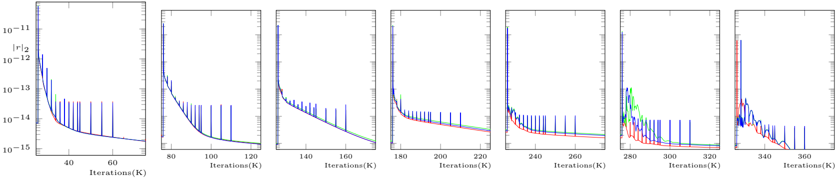







Baseline

- Iterations required don't increase with $L_r$
- Same pattern as supersonic/transonic cases
- Low Mach flow required more iterations in general
- Reasonable, predictable cost ($t_{CPU}/N_{grid}$ insensitive)
- Well converged solutions ($\mapsto$ continuous)




$L_r = 1$ $L_r = 2$ $L_r = 3$ $L_r = 4$ $L_r = 5$ $L_r = 6$ $L_r = 7$

# Conclusions

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- AMR exercised on subsonic, transonic and supersonic flowfields
- Solutions did not require more iterations as $L_r$ increased
- Shocks and separated regions were regions with most effect
- AMR provided great efficiency in getting high accuracy answers

Can now pass to continuous limit (turbulence model dev. requirement)

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From here...

- Utilize technique in turbulence modeling work going forward ($R_{ij}$, $T_{ijk}$ models — $\partial u_i$ details more important)
- 3D flow: CRM, FAITH hill,...? (Revisit Chow-Zilliac—Vortices)
- AMR for unsteady flows would be wonderful.